



# Liquid Belt Radiator Design Study

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## SUMMARY

The Liquid Belt Radiator (LBR) is an advanced concept developed to meet the needs of anticipated future space missions. A previous study completed by Arthur D. Little, Inc. for the NASA-Lewis Research Center documented the advantages of this concept as a lightweight, easily deployable alternative to present day space heat rejection systems. A conceptual drawing of the LBR is shown in Figure S.1.

The program documented in this report represents a continuation of the aforementioned work. The technical efforts associated with this study concentrated on refining the concept of the LBR as well as further examining key design issues identified through consultations with NASA-Lewis. The following briefly summarizes the results of these investigations.

A parametric evaluation of the LBR for low, intermediate, and high temperature heat rejection levels and various working fluids was completed. The low temperature (300-350 K) case assumed the use of both diffusion pump oils and gallium as the working fluids. The intermediate temperature (453 K) assumed the use of lithium or gallium while the high temperature case (~ 505 K) assumed the use of tin or gallium.

As was determined in Phase I, both the working fluid emissivity and radiating temperatures greatly impact the required size and total system mass of a particular option. In the low temperature case, the relationship between emissivity, material vapor pressure, and mission duration become especially intricate. For example, for the temperatures considered and with missions less than four years, the use of diffusion pump oils (Santovac-6) resulted in a lower mass system than 0.1 emissivity gallium. The opposite was true for missions of over 4 years duration. The reason for this was the loss of oil due to evaporation which required a makeup supply. By comparison, gallium has a negligible vapor pressure at all temperatures considered.

# LIQUID BELT RADIATOR

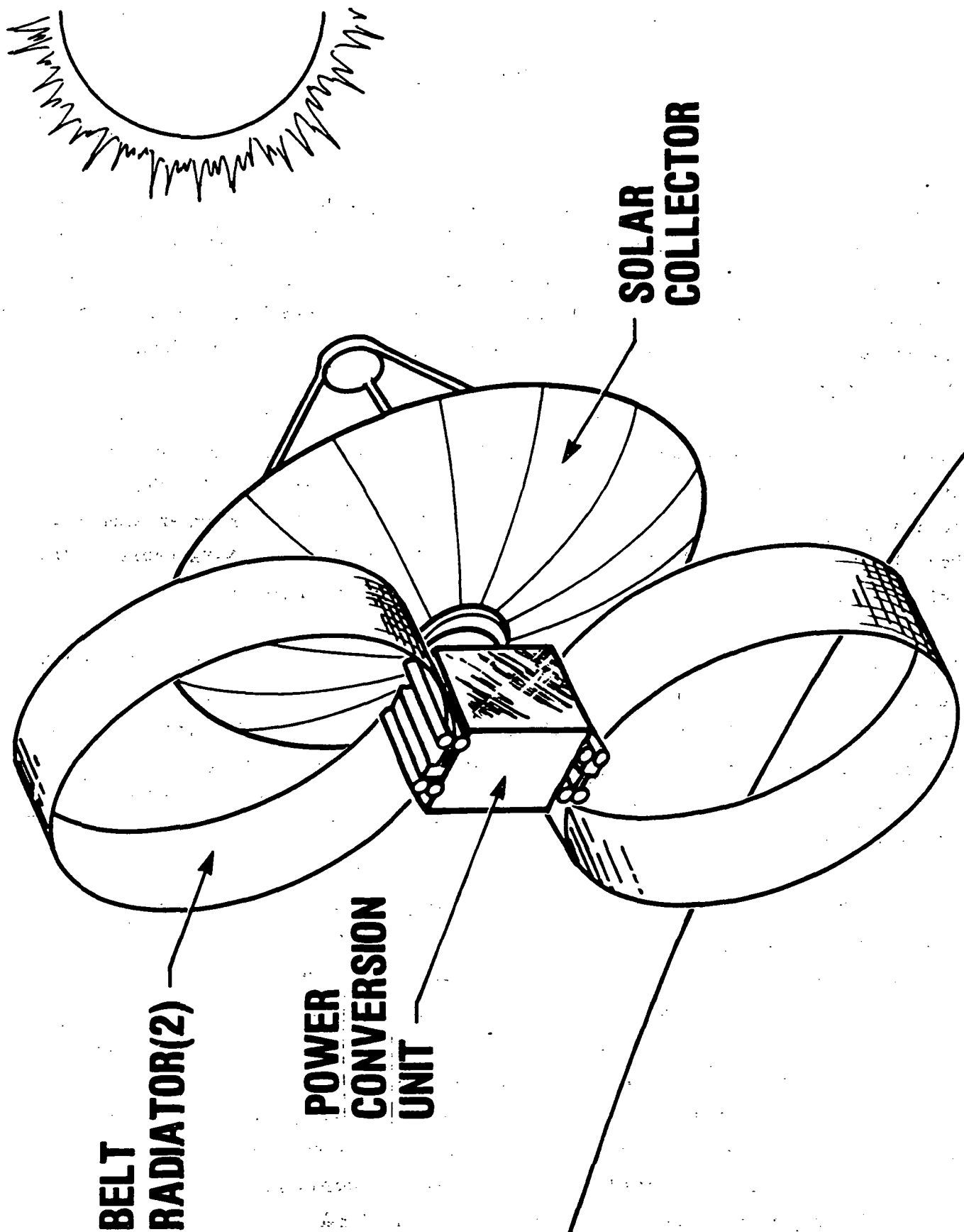


Figure S.1 LIQUID BELT RADIATOR CONCEPTUAL DRAWING

A preliminary study of LBR dynamics stability considerations was also completed. This initial analysis assumed no radial stiffness - a very conservative assumption especially when phase change operation is considered. The major conclusion of this study was that the LBR structure will deform into a catenary-like shape under the influence of an acceleration field. When the field goes to zero however, the LBR will return to its normal equilibrium cylindrical shape. The amount of deflection associated with actual dynamic loads must be examined in greater detail and within NASA guidelines. Such efforts undoubtedly will necessitate the use of finite element numerical analysis techniques.

The Phase I effort was used as the basis for preparing an updated system point design. This point design was undertaken for the low temperature case assuming the use of diffusion pump oil, Santovac-6, as the heat transfer media. Additional analytical and design effort was directed toward determining the impact of interface heat exchanger, fluid bath sealing, and belt drive mechanism designs on system performance and mass.

The updated design supported the Phase I results by indicating a significant reduction in specific system mass as compared to heat pipe or pumped fluid radiator concepts currently under consideration ( $1.3 \text{ kg/m}^2$  versus  $5 \text{ kg/m}^2$ ). The updated design also indicated that motor drive parasitic power losses associated with belt motion through the interface heat exchanger remained low ( $< 1 \text{ kw}$ ). It should be noted that parasitic power losses for liquid metal systems would be negligible due to their very low viscosity.

The updated point design along with the parametric analyzes provide a sound basis for undertaking further development of the LBR system and serve to reinforce the earlier conclusions that the LBR concept should be considered as a strong candidate for lightweight space radiators through the complete temperature range of current interest.

## 1.0 INTRODUCTION

This report is a continuation on work previously completed under NASA contract no. NAS3-22253.MOD2. In the previous program, henceforth referred to as Phase I, a preliminary point design of LBR was developed, which indicated that the LBR concept offers the advantages of low mass, compact stowage, and automatic deployment.

The objectives of this follow-on contract (NAS3-23889) were to further refine the parametric analyses for a range of working fluids and operating temperatures and to examine more closely fluid bath contaminant, belt drive system, and dynamic issues identified in the Phase I work. The program was divided into three separate tasks:

- o Task 1: Parametric Evaluation of Alternative LBR  
Operating Specifications
- o Task 2: Preliminary Belt Dynamic Analysis
- o Task 3: LBR Design Issues/Point Design Preparation

The following chapters of this document present the results of these tasks. Chapter 6 is the summary of the important conclusions of this work and the presentation of a research and development plan for taking the conceptual LBR design to a hardware development project dedicated for a Shuttle-based test flight.

## 2.0 PARAMETRIC EVALUATIONS OF ALTERNATE LBR DESIGNS

### 2.1. Background

This chapter describes the results of Task 1.0 to undertake parametric analysis of the performance characteristics of high temperature LBR systems. This effort draws heavily on the background gained in developing a low temperature baseline radiator design in the Phase I program and is described in the report entitled "Preliminary Evaluation of a Liquid Belt Radiator for Space Applications".\*

### 2.2. Cases Considered

Table 2.1 shows the cases considered in this study and Figures 2.1, 2.2 and 2.3 the associated temperature profiles. These divide as follows:

#### A. Low Temperature Case

Two materials were considered for low temperature heat rejection, namely Santovac-6 and gallium. Santovac-6 was also assumed as the belt fluid in the previous study described in Reference 1. For both cases it was assumed that the radiator was dissipating heat from a Brayton power cycle with the heat rejection temperature profile indicated in Figure 2.1. The temperature ranges used for the Santovac 6 LBR scenarios were determined by the need to maintain evaporative losses within an acceptable range. This placed a limit of about 350°F on the upper temperature of LBR operation. Both sensible and latent heat modes were considered for gallium. In the sensible heat mode the gallium temperature could more closely follow the heat rejection temperature profile since the vapor pressure of gallium is close to zero at these temperatures. This, in turn, results in the gallium operating at a higher

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\* Henceforth referred to as Reference 1.



Table 2.1

SCENARIOS CONSIDERED FOR TASK 1 PARAMETRIC ANALYSIS

<u>Material</u>	<u>Temperature (K)</u>	<u>Heat Rejection Type</u>	<u>Assumed Emissivity</u>
<u>Latent Heat Cases</u>			
Gallium	303	Low	0.1
Gallium	303	Low	0.3
Lithium	453	Intermediate	0.1
Lithium	453	Intermediate	0.3
Tin	505	High	0.1
Tin	505	High	0.3
<u>Sensible Heat Cases</u>			
Santovac-6	310-350	Low	0.8
Santovac-6	300-350	Low	0.8
Gallium	310-450	Low	0.1
Gallium	310-450	Low	0.3
Gallium	510-650	High	0.1
Gallium	510-650	High	0.3
Gallium	435-505	High	0.1
Gallium	435-505	High	0.3

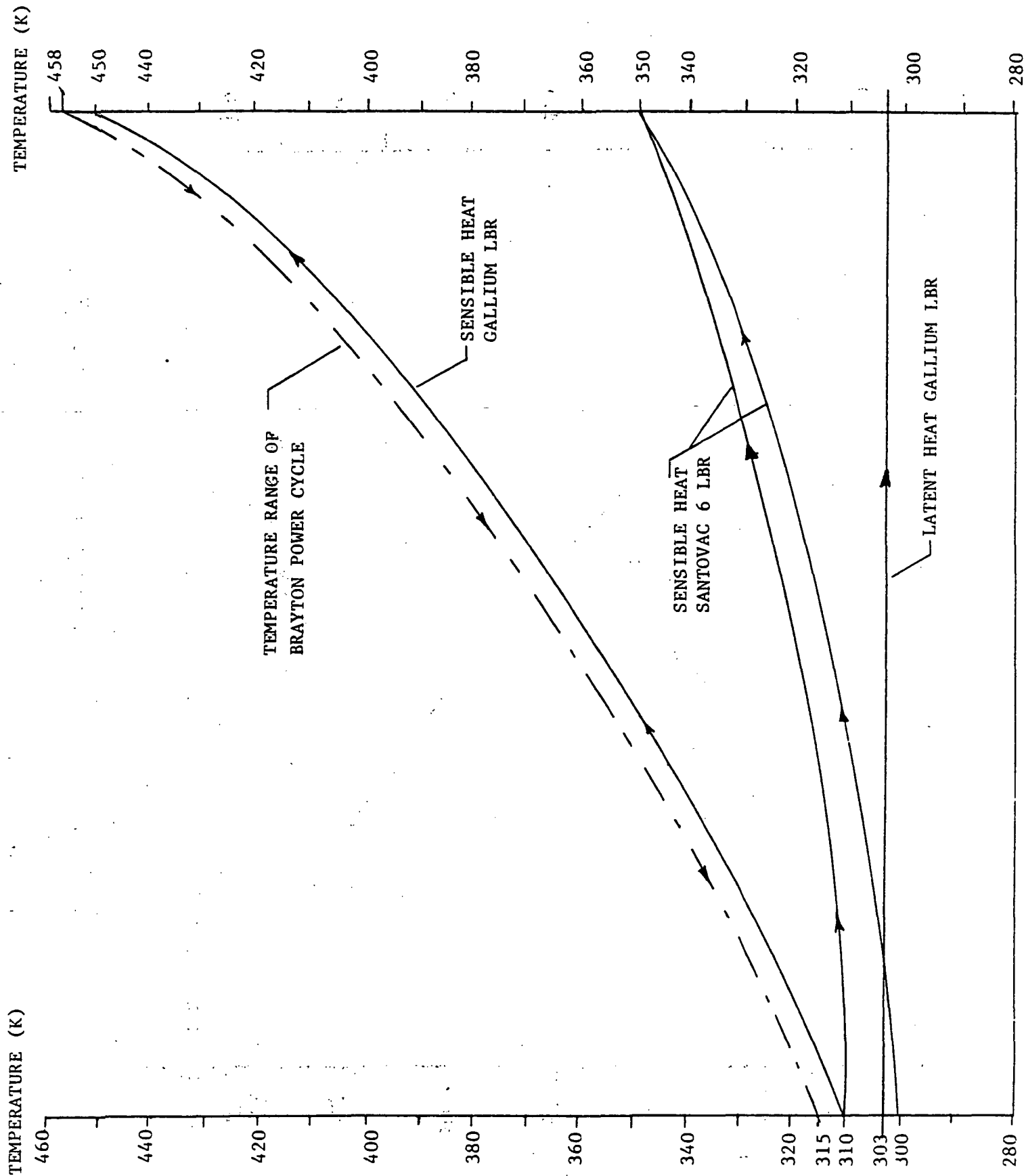


Figure 2.1 LOW TEMPERATURE HEAT REJECTION OPTIONS

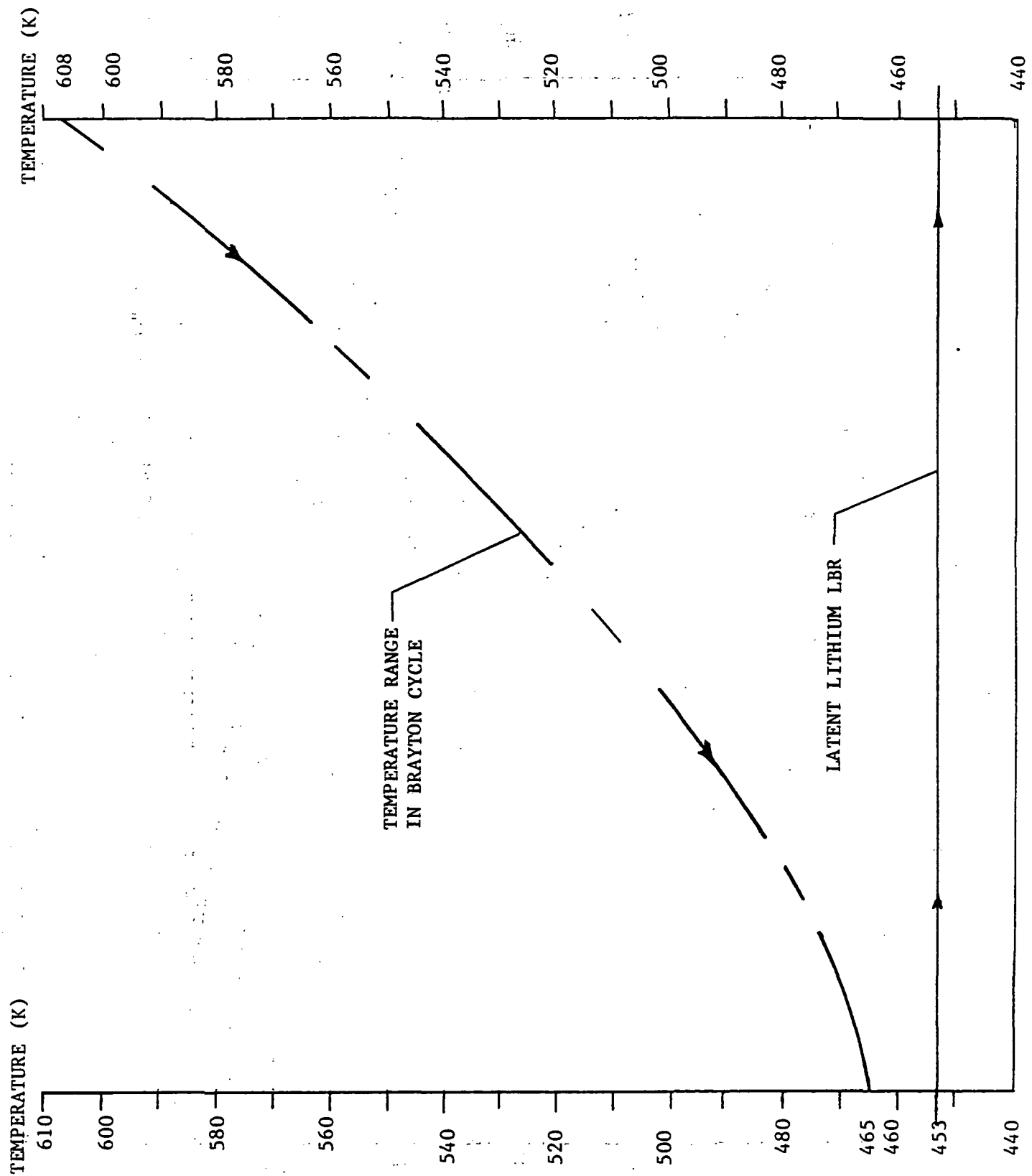


Figure 2.2 INTERMEDIATE TEMPERATURE HEAT REJECTION OPTIONS

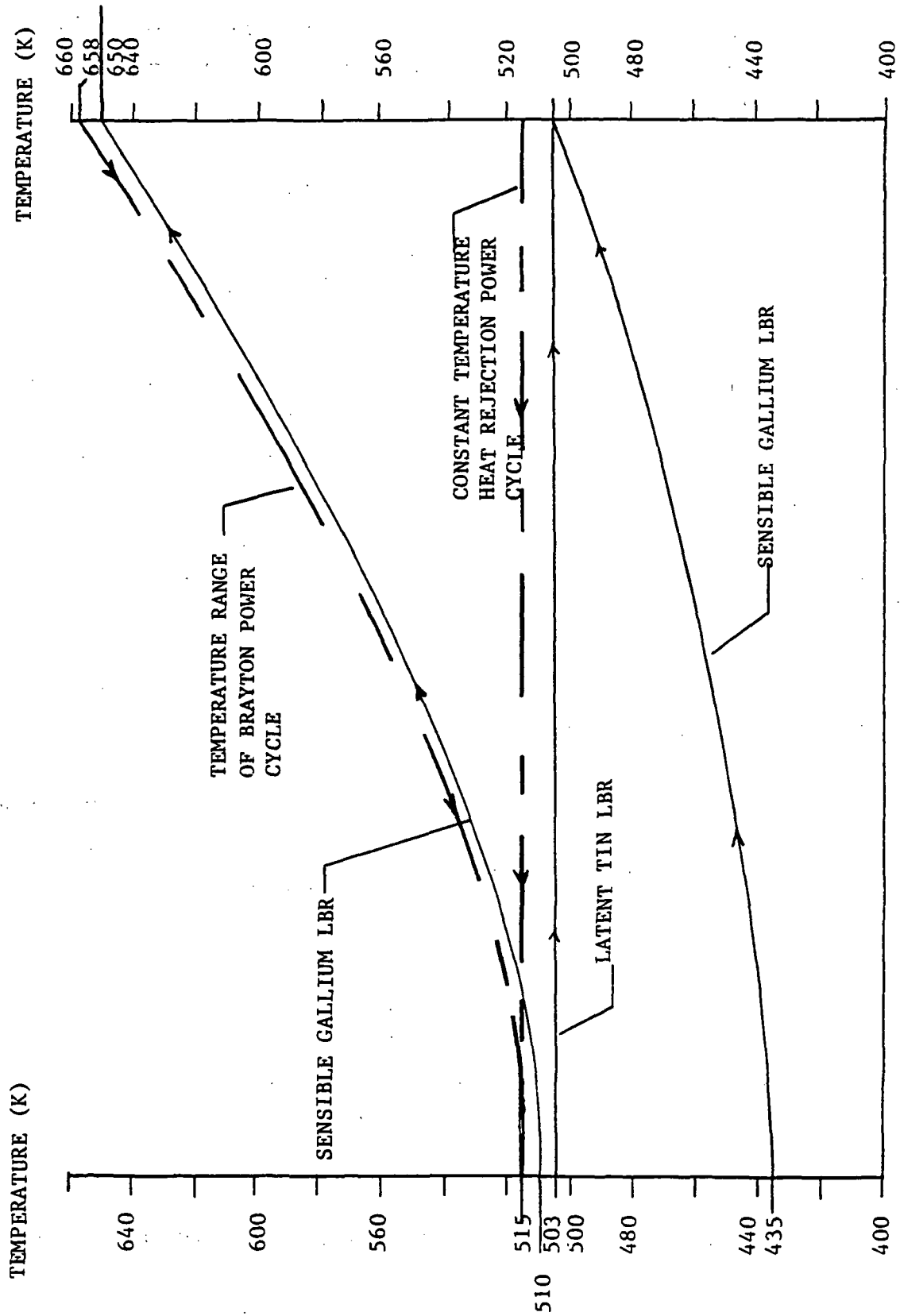


Figure 2.3 HIGH TEMPERATURE HEAT REJECTION OPTIONS

average temperature than the Santovac-6. In the latent heat mode, the gallium operates at a constant temperature equal to its melting point (303 K).

#### B. Medium Temperature Case

Reference 1 indicates that lithium may be an excellent material for use in an LBR due to its low density and very high heat of fusion. As indicated in Figure 2.2, a lithium LBR operating in a latent heat mode could be used to dissipate heat from Brayton as well as Stirling, or liquid metal Rankine power cycles at intermediate temperature levels.

#### C. High Temperature Case

As indicated on Figure 2.3, three high temperature cases were considered:

- o Tin operating in a latent heat mode (505 K)
- o Gallium operating in a sensible heat mode over a temperature range of 510 K to 650 K corresponding to use with a high temperature Brayton cycle.
- o Gallium operating in a sensible heat mode over a temperature range of 435 K to 505 K corresponding to a high temperature power cycle rejecting heat over a narrow temperature range (for example, liquid metal Rankine).

### 2.3 Assumptions and Material Physical Characteristics

The details of the analytical approach used to estimate radiator areas, belt speeds, parasitic losses, and evaporative losses are presented in Reference 1. These operational parameters depend critically on:

- o Material Characteristics such as emissivity, specific heat, heat of fusion, density, and viscosity.
- o Operating Requirements such as heat dissipation rate, operating temperature ranges, and background temperature level.

Table 2.2 summarizes the major assumptions in both categories used in the parametric studies of this report. While most of the material characteristics were drawn from referenced sources, very little information was available on their emissivities (this excludes Santovac-6 which was measured to be 0.8 as part of the Phase I effort). For purposes of analysis two values of emissivity were considered for the metals: 0.1 and 0.3. As indicated in Reference 1, the value of emissivities for absolutely pure metals may be lower than this range. Based on limited measurements in Phase I, however, it appears that with modest levels of impurities or alloying emissivities in this range can be obtained - particularly in the solid state which would exist on the belt surface for the latent heat modes of operation.

The operating requirements, particularly the heat rejection rate of 75 kW and background temperature of 250K (which implies low earth orbit) were the same as those used in Phase I. For all the cases examined, the specific gravity of the screen mesh material was assumed comparable to that of the working fluid. In addition, these mesh/fluid combinations were all assumed to have wetting behavior.

#### 2.4. Calculational Procedure

All parametric analyses assumed the same radiator configuration as presented in Phase I. In this design the LBR is cylindrical in its deployed position. The mesh is drawn through a heat exchanger containing the liquid or molten heat transfer medium which in turn radiates to space and dissipates the waste heat. In its stowed position the mesh is contained in a "stuffing box" and can be deployed either mechanically or pneumatically once in an established orbit. Figure 2.4 displays this design in both the displayed and stowed position.

The parameters of primary interest in establishing the characteristics of the system are:

- o The area and mass of the LBR and its associated dimensions.
- o The size and mass of the heat exchanger system where heat is transferred into the LBR.

Table 2.2

TASK 1 LIQUID BELT RADIATOR DESIGN PARAMETER ASSUMPTIONSo Major Variables

- $\epsilon$  : Working Fluid Emissivity  
 $T_{\max}$  : Maximum Belt Temperature  
 $T_{\min}$  : Minimum Belt Temperature  
 $T_i$  : Power Cycle Working Fluid Initial Temperature  
 $T_f$  : Power Cycle Working Fluid Final Temperature

o Fixed Parameters (For all scenarios)

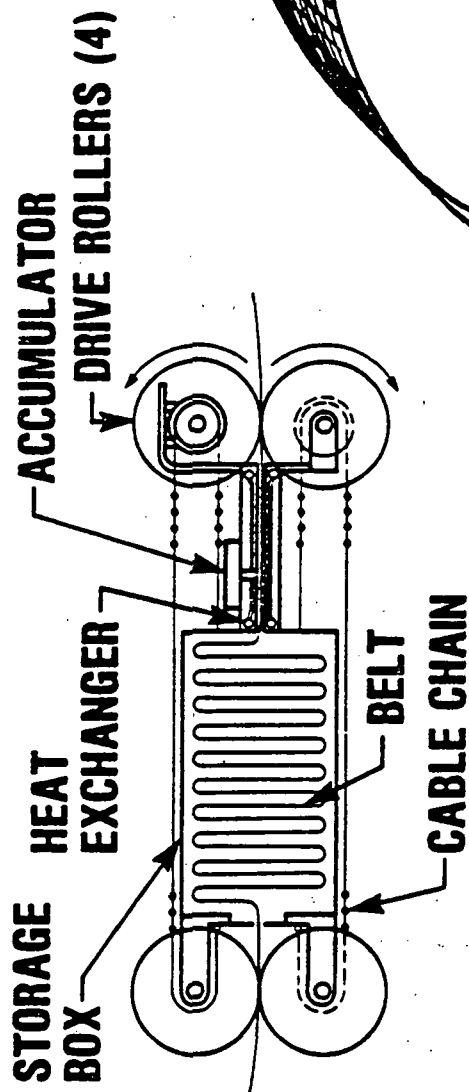
- $Q$  : Heat to be Rejected = 75 kW  
 $F_{RS}$  : View Factor = 0.9  
 $t_{LM}$  : Thickness of Liquid Metal LBR =  $1.3 \times 10^{-4}$  m  
 $t_{oil}$  : Thickness of Oil LBR =  $5.1 \times 10^{-4}$  m  
 $U_{LM}$  : Overall Heat Transfer Coefficient of Liquid Metal LBR = 5.70 kW/kgK  
 $U_{oil}$  : Overall Heat Transfer Coefficient of Oil LBR = 0.57 kW/kgK  
 $a$  : Heat Exchanger Gap Thickness =  $5.8 \times 10^{-3}$  m

o Working Fluid Properties

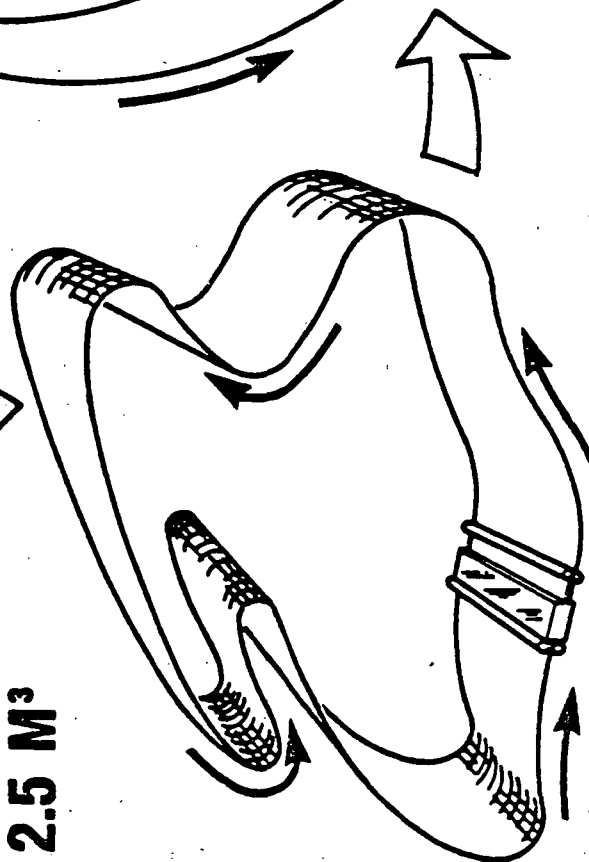
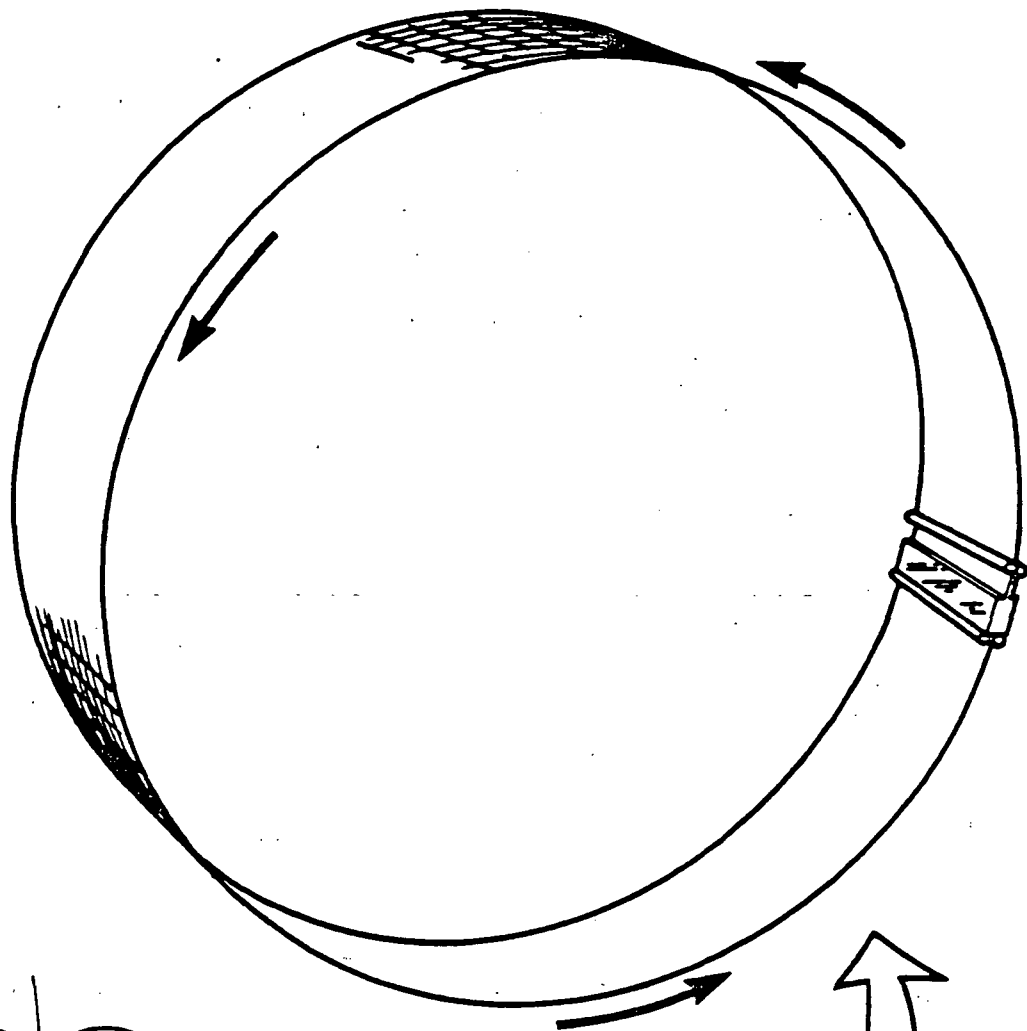
	<u>Gallium</u>	<u>Lithium</u>	<u>Tin</u>	<u>Santovac-6</u>
Density ( $\text{kg/m}^3$ )	6100	530	7300	1240
Specific Heat (kW/kgK)	0.34	3.47	0.23	1.55
Latent Heat (kJ/kg)	82.1	663.0	60.3	NA
Molecular Weight	69.7	6.9	118.7	538
Vapor Pressure (torr) <sup>1</sup>	(14700, 10.1)	(8415, 11.34)	(15500, 8.2)	Ref 1
Dynamic Viscosity <sup>2</sup> $10^{-3}$ (Ns/m <sup>2</sup> )	(0.44, 481)	(0.15, 669)	(0.54, __)	Ref 1

- Refers to the terms (A,B) from the general equation  $\log P_v = B-A/T$ ;  $T_{\text{abs}}$ . From from Smithells Metals Reference Book, Sixth Edition, pp. 8-54, 8-56.
- Refers to the terms ( $\eta_o, E$ ) from the general equation  $\mu = \eta_o e^{(E/T)}$ ;  $T_{\text{abs}}$ . From from Smithells Metals Reference Book, Sixth Edition, pp. 14-7, 14-8.

# LIQUID BELT RADIATOR



**STORAGE  
VOLUME  
2.5 M<sup>3</sup>**



**AUTOMATIC DEPLOYMENT**

**TOTAL RADIATING AREA 290 M<sup>2</sup>**

Figure 2.4 LBR OPERATIONAL SCHEMATIC; PRELIMINARY DESIGN



- o The parasitic losses associated with moving the LBR through the molten material in the heat exchanger.
- o The evaporative losses of the LBR which:
  - Require make-up material to replenish that lost during long missions.
  - Can have damaging effects by virtue of the evaporated material depositing on sensitive areas of the spacecraft.

The analysis for calculating the above parameters are presented, in detail, in Reference 1. In order to facilitate the parametric analyses the governing equations have been programmed on a Hewlett Packard HP-11C calculator.

## 2.5 Discussion of Results

Tables 2.3 and 2.4 summarize the results of the analyses. Several observations on these results include:

### 2.5.1 LBR Area

The area of LBR is inversely proportional to the emissivity. In the low temperature case, for example, there is a significant mass advantage for the Santovac-6 oil LBR ( $\epsilon = 0.8$ ) operating from 300-350K. This design has a single sided area of  $115 \text{ m}^2$  and weight of about 72 kg.

However, liquid gallium operating over a wide temperature range (310-450K) results in similar areas and masses ( $136 \text{ m}^2$ , 88 kg) if its emissivity approaches 0.3. This is due to the higher average temperature associated with the gallium LBR made possible by the negligible vapor pressure of gallium in this temperature range.

### 2.5.2 Parasitic Power

Parasitic power is primarily associated with the viscous drag resulting from moving the LBR through the liquid within the interface heat exchanger. The Santovac-6 has a viscosity approximately 1000 times greater than that of the liquid metals. The viscous drag even for the Santovac-6 is quite low and results in parasitic power of less than 0.5 kW. Due to the aforementioned low viscosities of the liquid metals, the viscous drag for the LBR using

Table 2.3

TASK 1 PARAMETRIC RESULTSLOW TEMPERATURE HEAT REJECTION

Working Fluid	Santovac-6	Santovac-6	Gallium	Gallium	Gallium	Gallium
Mode of Operation	Sensible	Sensible	Latent	Latent	Sensible	Sensible
Emissivity	0.8	0.8	0.1	0.3	0.1	0.3
Heat Rejection Rate	75	75	75	75	75	75
Exit Temperature (K)	350	350	303	303	450	450
Inlet Temperature (K)	310	300	303	303	310	310
Belt Width (m)	2.9	3.02	11.37	6.59	5.21	3.00
Belt Thickness (cm)	0.051	0.051	0.013	0.013	0.013	0.013
Belt Circumference (m)	36.45	37.98	142.91	82.51	65.45	37.79
Belt Diameter (m)	11.6	12.09	45.59	26.26	20.83	12.03
Belt Area (m <sup>2</sup> )*	105.75	114.79	1625.16	541.72	340.88	135.63
Belt Mass (kg)	66.61	72.3	1259.0	419.7	264.1	88.0
Belt Speed (m/s)	0.7	0.5	0.1	0.2	0.4	0.7
Yearly Material Loss(kg)	70	56	~0	~0	~0	~0
Heat Exchanger Length (m)	0.68	0.46	0.01	0.02	0.20	0.34
Heat Exchanger Single Sided Gap Distance (cm)	0.57	0.57	0.57	0.57	0.57	0.57
Parasitic Power (kW)	0.42	0.22	~0	~0	0.0002	0.0005
Orbital Drag (N)	0.0009	0.009	0.0131	0.0044	0.0027	0.0009

\* Refers to Single Sided Area.

Table 2.4

## TASK 1 PARAMETRIC RESULTS

Working Fluid	INTERMEDIATE TEMPERATURE HEAT REJECTION		HIGH TEMPERATURE HEAT REJECTION					
	Lithium Latent	Lithium Latent	Tin Latent	Tin Latent	Gallium Sensible	Gallium Sensible	Gallium Sensible	Gallium Sensible
Mode of Operation	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3
Emissivity	75	75	75	75	75	75	75	75
Heat Rejection Rate	453	453	505	505	650	650	505	505
Exit Temperature (K)	453	453	505	505	510	510	435	435
Inlet Temperature (K)	3.91	2.26	3.09	1.79	2.03	1.17	3.35	1.93
Belt Width (m)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Belt Thickness (cm)	49.17	28.39	38.87	22.44	25.52	14.73	42.0	24.3
Belt Circumference (m)	15.65	9.04	12.37	7.14	8.12	4.69	13.40	7.73
Belt Diameter (m)	192.39	64.13	120.23	40.08	51.83	17.28	140.6	46.9
Belt Area (m <sup>2</sup> )	12.95	4.31	111.47	37.16	40.16	13.39	108.9	36.3
Belt Mass (kg)	0.4	0.7	0.43	0.75	0.99	1.72	1.21	2.08
Belt Speed (m/s)	0.091	0.031	~0	~0	~0	~0	~0	~0
Yearly Material Loss(kg)	0.03	0.05	0.04	0.07	0.51	0.88	0.06	0.10
Heat Exchanger Length(m)	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Heat Exchanger Single Sided Gap Distance (cm)	~0	~0	~0	~0	~0	~0	~0	~0
Parasitic Power (kW)	0.0015	0.0005	0.001	0.0001	0.0007	0.002	0.0002	0.0007
Orbital Drag (N)	0.0015	0.0005	0.001	0.0003	0.0004	0.0001	0.0001	0.0004

(1) Refers to single sided area.

these materials will be very low - ideally measured in watts. As a practical matter, therefore, parasitic power needs of the LBR are not in themselves a major factor and impose only limited design constraints on the system.

### 2.5.3 System Mass

Table 2.5 summarizes the system masses for all the scenarios of Table 2.1 including the rollers, motors, and heat exchanger. For purposes of this parametric analysis it was assumed that:

- o Motors for the liquid metal LBR (with very low viscous drag) have a mass of 8.8 lb (4 kg) each.
- o The heat exchanger belt drive rollers, and stowage container masses are proportional to LBR width and the same as estimated in Phase I (i.e., the dimensions in direction of belt movement are held constant).
- o The deployment means adds very little to the system mass.

The Phase I study indicated that the belt/heat transfer fluid comprise over 50% of system mass. Modest uncertainties in the estimated mass of other system components should not have a major impact on overall system mass estimates - at least for purposes of these initial parametric analyses.

The system masses indicated on Table 2.5 result in specific masses for the LBR which compare very favorably with alternatives. For example, for the Santovac-6 radiator operating from 300-350K, the system mass per unit prime radiating area (i.e., specific mass) is  $1.1 \text{ kg/m}^2$  as compared to  $5 \text{ kg/m}^2$  currently projected for heat pipe or pumped fluid systems. The higher temperature liquid metal systems have specific masses in the range of 0.6 through  $1.3 \text{ kg/m}^2$  assuming an emissivity of 0.3. This also compares favorably with heat pipe or pumped fluid systems.

### 2.5.4 Mass Loss/Optimum System Design

As indicated in Tables 2.3 and 2.4, the material loss of the metal systems is negligibly low for all cases considered. The same however can not be said

Table 2.5

SYSTEM MASS AND SPECIFIC MASS DETERMINATIONS FOR TASK I SCENARIOS

<u>SCENARIO</u>	<u>OPERATING EMISSIVITY/</u>		<u>SYSTEM MASS</u> <sup>(1)</sup>	<u>SPECIFIC MASS</u> <sup>(2)</sup>
	<u>TEMPERATURE RANGE</u>	(K)		
			(kg)	(kg/m <sup>2</sup> )
Sensible Santovac	0.8/310-350		229.3	1.20
Sensible Santovac	0.8/300-350		224.1	1.08
Latent Gallium	0.1/303		1570.7	0.54
Latent Gallium	0.3/303		603.3	0.62
Sensible Gallium	0.1/310-450		410.7	0.67
Sensible Gallium	0.3/310-450		175.4	0.72
Latent Lithium	0.1/458		124.8	0.36
Latent Lithium	0.3/458		71.9	0.62
Latent Tin	0.1/505		201.3	0.93
Latent Tin	0.3/505		92.1	1.28
Sensible Gallium	0.1/510-650		101.6	1.09
Sensible Gallium	0.3/510-650		51.7	1.66
Sensible Gallium	0.1/435-505		205.68	0.81
Sensible Gallium	0.3/435-505		95.0	1.12

(1) Based on Reference 1; mass is for a one year mission.

(2) Specific mass defined per unit prime radiating area.

for Santovac-6. This low temperature oil loses over 70 percent of its original mass by evaporation each year when operating over the temperature range of 300-350K. This would necessitate a storage tank of Santovac oil to replace lost material during the mission. Figure 2.5 shows resultant LBR system mass as a function of mission length for the low temperature heat rejection cases using Santovac oil and gallium. As indicated, the system mass of the Santovac LBR (including make-up fluid) increases with mission life while that of the gallium options (sensible and latent heat) is constant. The crossover point ranges from less than 0.2 years to over four years depending on the emissivity values achieved for gallium operating in the sensible heat mode.

The weight loss of Santovac-6 could be reduced by lowering its peak operating temperature. This, however, increases radiator area requirements and mass. The optimal trade-off in operating conditions when using Santovac-6 would therefore depend on mission life requirements, mass allotments, and sensitivity to spacecraft contamination.

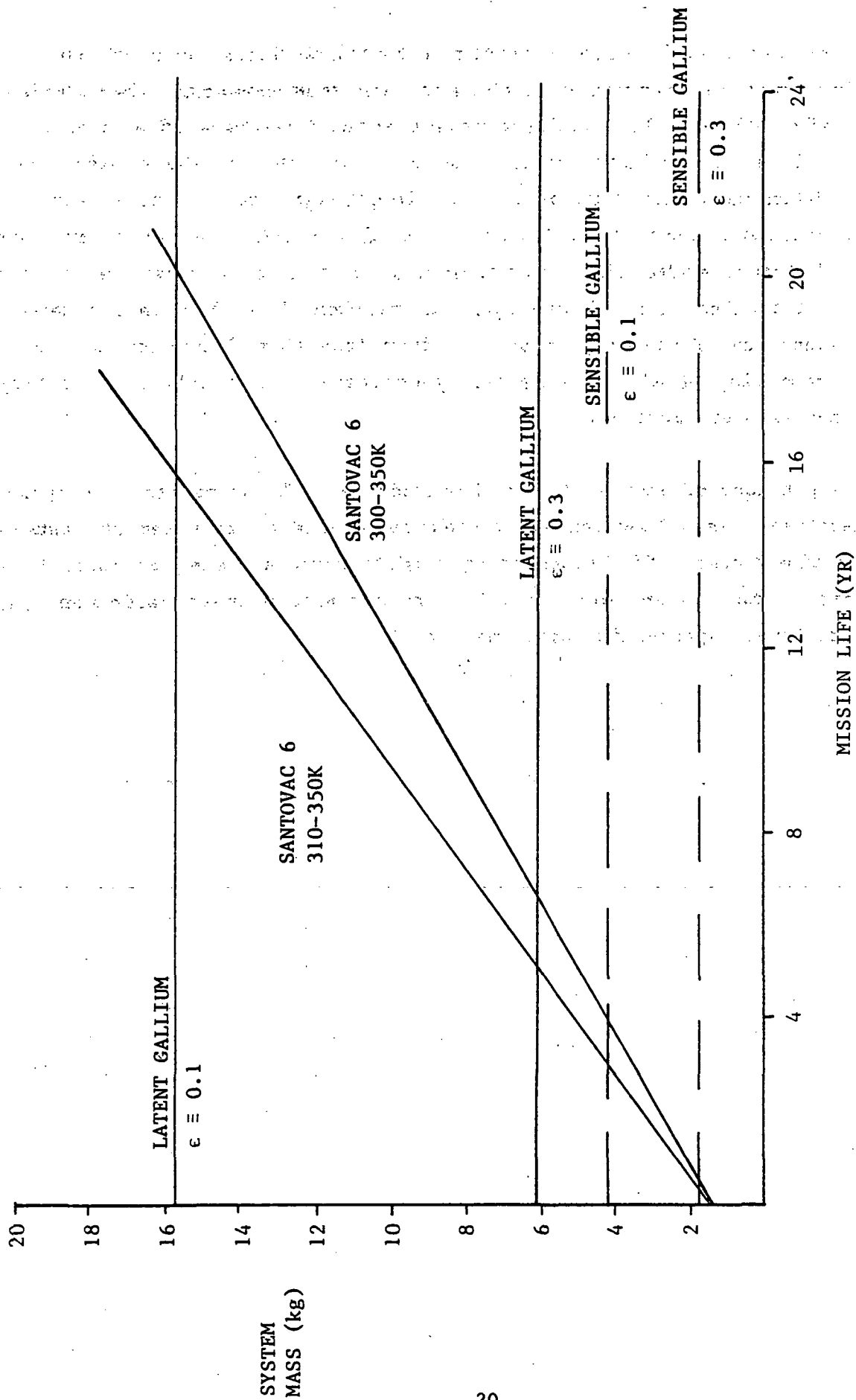


Figure 2.5 COMPARISON OF SYSTEM MASS vs MISSION LIFE FOR LOW TEMPERATURE HEAT REJECTION SCENARIOS ( $Q = 75$  kW).

### 3.0 PRELIMINARY LBR STABILITY ANALYSIS

This section documents the results of a preliminary LBR stability study (Task 2.0). In this analysis, the impacts of rectilinear accelerations on the cylindrical hoop structure of the present design were examined.

It was initially assumed that the belt structure had no stiffness in the radial direction although in reality the mesh structure would have limited compliance. This would be particularly true if a change of phase mode is utilized. In this case, the outer skin of the LBR is always solid (due to its first undergoing phase transformation) thereby adding measurable stiffness to the structure. Furthermore all accelerations were taken to be uniform and in the plane perpendicular to the LBR's rotational axis (i.e., in the plane of the belt).

Two situations were examined involving the existence of an acceleration with the belt at rest and then at constant velocity. In both cases the belt deforms into catenary-like shape, the extent of which depending on the level and duration of the acceleration. The resulting shape and the physics of this problem closely resemble the case of a flexible member (i.e., cable) under the influence of the earth's uniform gravitational field.

An important corollary of this preliminary investigation is the fact that although the belt deforms under loading, it returns to its normal cylindrical equilibrium shape when the acceleration field is removed. Thus it becomes particularly important to define both the acceleration magnitudes and durations. For example, if a "real" LBR (of limited, non-negligible stiffness) were subjected to an impulse type acceleration (short duration, large magnitude), it would deform only slightly. However, if this same acceleration magnitude were applied and sustained, the radiator would eventually collapse into the catenary shape previously discussed.



Key to any future analyses would be a rigorous model of the LBR structure. This model would include various stiffness parameters, particularly in case of phase change operation, and most likely would be based on circular beam theory. The impact of different steady state and transient loads on the dynamic shape of the radiator could easily be examined by this model. The results of these investigations in turn could then be utilized to determine the acceptability of LBR dynamics with respect to NASA Mission requirements or the need for stiffness enhancements and/or structural design modifications. For example, if dynamic loads existing at a platform are of sufficient magnitude to cause an unacceptable deflection (sustained or transient), a tethered conceptual design may be required. The tethered concept offers the dual advantage of both reduced dynamic interactions and a mitigation of potential contamination problems. In certain other applications, however, the compliance of the LBR under load may be extremely advantageous.

In summary, greater scrutiny of Liquid Belt Radiator dynamics is in order. These studies should include both deployment dynamics, and fully operational small and large deflection analyses. In addition, future mission requirements (i.e., heat rejection rates; allowable deflections, etc.) must be specified in order to fully determine their impact on LBR design, operation, and performance.

## 4.0 LIQUID BELT RADIATOR SYSTEM DESIGN STUDIES

### 4.1 Introduction

The point design of the Phase 1 program was updated taking into account additional analyses of issues associated with:

- o Containment/Seal Design;
- o Interface Heater Exchanger Design;
- o Stowage/Deployment System.

The updated designs have been prepared with the support of a CAD/CAM system which will facilitate the implementation of further design changes and improvements as the development program progresses.

### 4.2 Radiator Sizing

The size of the cylindrically shaped LBR point design is based upon the radiative heat transfer analysis documented in Reference 1. Like this previous study, the radiator is designed to operate over a temperature range of 300 - 330 K. The system utilizes Santovac 6 diffusion pump oil and a nylon screen mesh as working fluid/belt materials. The emissivity of the oil is conservatively assumed to be 0.8 and the cylindrical structure maintains a view factor to space of 0.9. In order to reduce the belt velocity and consequently lower parasitic power and motor sizing requirements, the thickness of the belt was increased to 0.076 cm (30 mils). Table 4.1 presents the salient dimensional parameters of the liquid belt radiator point design used in this study.

Table 4.1

## REVISED POINT DESIGN PHYSICAL DIMENSIONS AND OPERATING SPECIFICATIONS

Working Fluid : Santovac 6  
 Working Fluid Emissivity : 0.8  
 Mode of Operation : Sensible heat Rejection  
 Heat Rejection Rate : 75 kw  
 LBR View Factor to Space : 0.9

---

Exit Temperature : 330 K (135°F)  
 Inlet Temperature : 300 K (81°F)  
 Belt Width : 3.35 m (11 ft.)  
 Belt Thickness :  $7.64 \times 10^{-4}$  m (0.03 in.)  
 Belt Diameter : 13.70 m (45 ft.)  
 Belt Circumference : 43.0 m  
 Belt Area<sup>(1)</sup> :  $288.4 \text{ m}^2$  (3102 ft<sup>2</sup>)  
 Belt Prime Area<sup>(2)</sup> :  $\sim 260 \text{ m}^2$   
 Belt Mass : 0.53 m/s (1.75 fps)  
 Heat Exchanger Single Sided Gap Distance :  $5.8 \times 10^{-3}$  m (0.25 in.)  
 Yearly Evaporation Mass loss : 10.1 kg

---

Notes

- (1) Refers to inner and outer surface areas.  
 (2) Defined as the total area contributing to radiative heat transfer.

#### 4.3 Interface Heat Exchanger Design

The design of the interface heat exchanger is critical to the overall sizing of the LBR point design. For this application, heat must be transferred from a Brayton cycle to the heat rejection system. The working fluid of the power system is a helium-xenon mixture having a molecular weight of 44.55. This particular mixture is characterized by a very low thermal conductivity and hence poor heat transfer performance. An additional impediment to a direct heat exchanger design is the rigorous constraint allowing for only small gas side pressure drops.

For this reason, an intermediate coolant loop was viewed as the best means for transferring heat from the Brayton cycle to the LBR working fluid. For purposes of analysis, the intermediate loop was postulated to be lossless and operate between 310 to 450 K. This implies a log mean temperature difference (LMTD) of 44.3 K. Further review of the bath heat transfer mechanisms and the properties of Santovac-6 resulted in the heat exchanger length increasing to 0.73 meters as compared to 0.38 meters in the Phase I report. This reflects a more conservative assessment of heat transfer phenomena in the interface heat exchange liquid gap, and the desirability of minimizing LBR/HX temperature differentials. Additional analytical and experimental work will be refine interface heat exchanger design and identify means for further size and weight reductions. From Reference 1, the parasitic power based on a single sided gap distance of 0.64 cm (0.25 inch) may be calculated to be approximately 0.9 kilowatts. Despite the change in overall dimensional specifications of the LBR point design, it should be noted that the parasitic power calculated here is of the same order as that determined in the Phase I study.

The heat exchanger design is similar to that documented in Reference 1. The two heat exchanger plates are again 0.127 cm (0.05 inch) aluminum

sheet. The 134 tubes of the heat exchanger (67 per side) have a centerline separation distance of approximately 5 cm (2 inch) and diameters of 1.27 cm (0.5 inch). These tubes are designed to be vacuum brazed to the heat exchanger plates in order to establish good thermal contact. The mixing header (2.86 cm (1.125 inch) diameter) acts to divide the flow evenly between all the tubes so that each contributes equally to the heat transfer process. The Santovac oil "bath", or region through which the belt moves, is defined as the volume bounded by the heat exchanger plates and two aluminum channels 1.27 cm in height. From the dimensional specifications, the total volume of the bath is  $0.036 \text{ m}^3$  ( $1.27 \text{ ft}^3$ ).

Thin walled aluminum piping is included in the heat exchanger design to interconnect the intermediate coolant loop with the LBR working fluid and the Brayton cycle helium-xenon gas mixture. Analysis of both the intermediate cooling loop and Brayton side heat exchanger have not been included in this study. Typically these items are the responsibility of power cycle designers and do not fall under the province of radiator development.

#### 4.4 Seal Design

An important issue raised in the Phase 1 effort was the requirement to prevent the leakage of Santovac 6 working fluid from the heat exchanger bath as a result of viscous forces imposed by belt motion.

Figure 4.1 is a schematic of a seal design to accomplish this task. The seals act to close off the Santovac oil "bath" discussed in Section 4.3. As can be seen in the figure, a double seal design is employed at both the top and bottom of the belt. This configuration is repeated at the rear (i.e., belt entrance) of the LBR.

The seal design indicated is based upon configurations manufactured by the Seal-Master Corporation. For this application, a plastic spring

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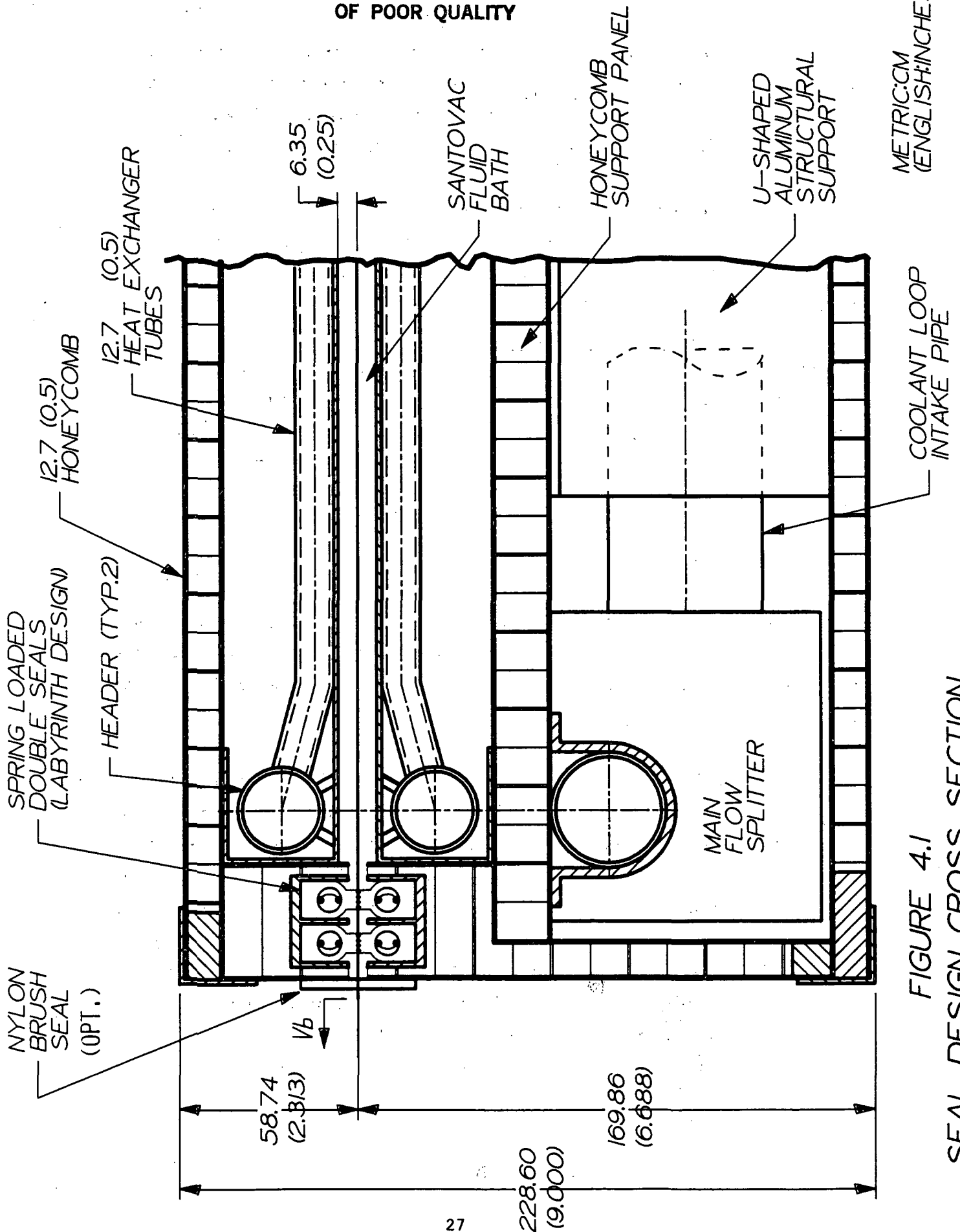


FIGURE 4.1  
SEAL DESIGN CROSS SECTION

element is used to lightly load the seal against the moving belt ensuring good contact between this element and the belt. The contact portion of the seal is labyrinth in nature and the use of four sealing members per belt exit/entrance slot will enhance sealing performance.

For the low temperature applications the seals can be manufactured from a number of non-metallic materials (nylon, rulon, carbon composites) which are used extensively in advanced thermomechanical systems such as Stirling engines and compressors. The low belt velocities and the lubrication effects of the oil should result in an approximate zero wear condition for the seals and thus long life. The entire seal package (all four double seal elements) has a mass of approximately 8 kilograms, due to the use of light weight structural materials (i.e., aluminum, honeycomb, rubber, plastics) and modest amounts of aluminum reinforcements.

#### 4.5 Drive System Design

The nylon belt is driven at a linear velocity of approximately 0.5 meters/second (1.75 ft/sec). The power required to overcome the viscous and sealed induced drag was calculated in Section 4.3, to be less than 1.0 kW.

Views of the front and rear sections of the belt drive system are shown in Figures 4.2 and 4.3. The system features two space worthy 1.75 horsepower DC brushless motors which drive a gear based speed reduction system. The gears are stainless steel and are impregnated by a bake and cure technique with a dry lubricant. The entire motor power train has an efficiency of between 75 and 85%. The DC power supply of the spacecraft (25 VDC nominal) provides the power to each motor. These motor designs are similar to existing product lines manufactured by the MPC Corporation.

Each gearhead motor is approximately 15.2 cm (6 inch) long, and 10.2 cm (4 inch) in diameter and has a weight of 7 kilograms. The two motors are used in this design in order to increase system reliability via redundancy. A magnetic clutch mechanism at the front of each motor controls the actuation of one or the other, since each unit is designed to meet the total drag load of approximately 1675 N (approximately 375 lbf). The motors will be designed to have radiative cooling "fins" and thermal conduction paths to the internal windings in order to dissipate heat generated by inefficiencies. All motor and shaft bearing elements are comprised of nonlubricated graphite materials which have been proven in space applications. In all sizing estimates, bearing drag was assumed to be negligible compared to that associated with viscous interactions.

When operating, a given motor drives two 10 cm (4 inch) diameter nylon sprockets as well as two timing pulleys and synchronous belts located at the front (i.e, belt exit) of the LBR (figure 4.2). The rotational speed of the sprockets and pulleys is 100 RPM. Beneath the drive sprockets are two smaller slave rollers which rotate in response to the belt's motion. The synchronous belt drive runs the length of the LBR positively coupling the rear drive components. This rear drive or idler system is comprised of similar master/slave drive sprockets and mating timing pulleys. Two aluminum rollers, located at the front and rear, span the LBR's width. The rollers are 7.6 cm (3 inches) in diameter and have a thickness of approximately 0.1 cm (0.035 inches). These rollers act to resist torsional stresses, thereby eliminating phase differences between opposite front and rear end drive sprockets.

The front and rear drive systems, including motors, are incorporated on a 1.27 cm (0.5 inch) thick honeycomb panel which is fixed to the external support panels of the LBR heat exchanger assembly. The tread of the nylon belt is designed to be 0.79 cm (2 inch) wide in order to reduce stresses arising from drive sprocket contact. The tread itself



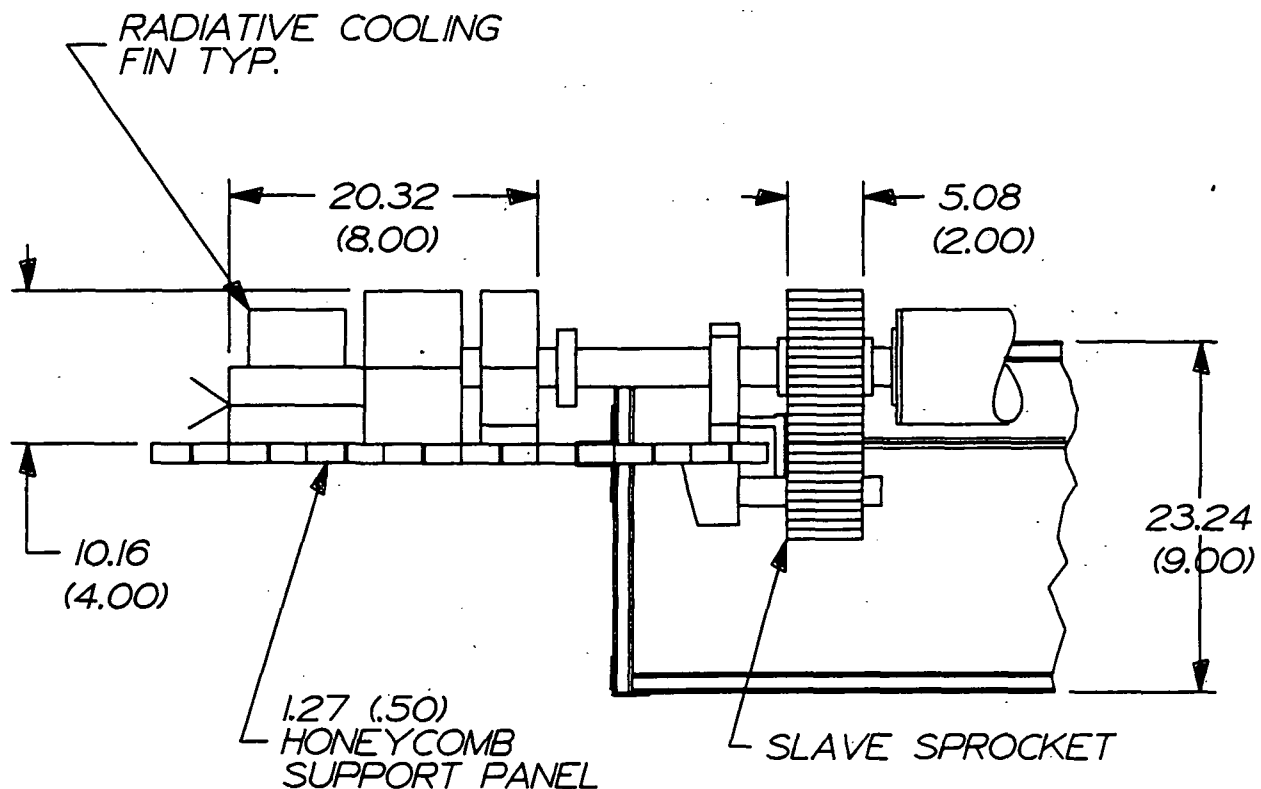


FIGURE 4.2A  
FRONT VIEW

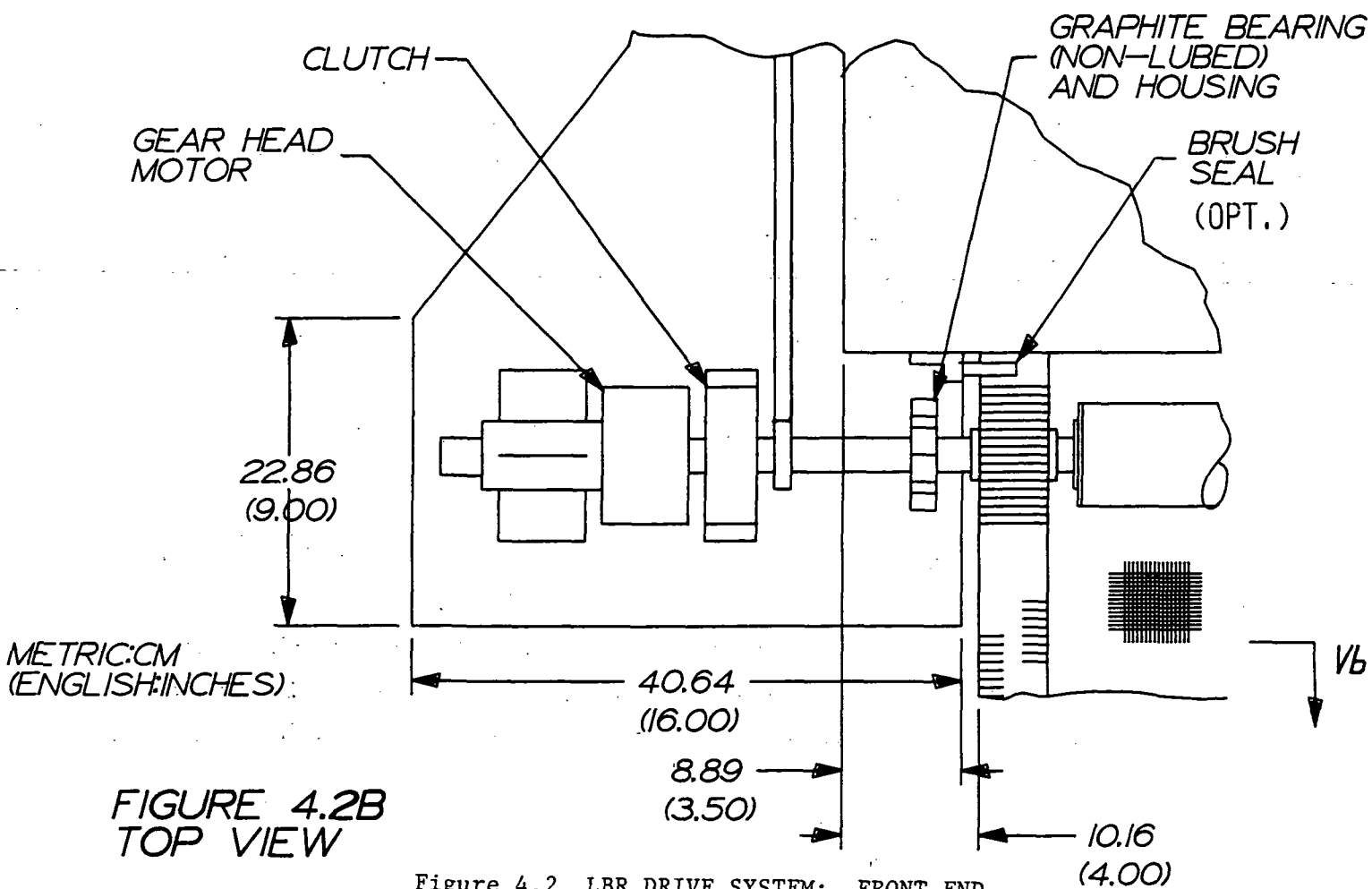


FIGURE 4.2B  
TOP VIEW

Figure 4.2 LBR DRIVE SYSTEM: FRONT END

GRAPHITE BEARING  
(NON LUBED)  
AND HOUSING

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SYNCHRONOUS  
BELT PULLEY

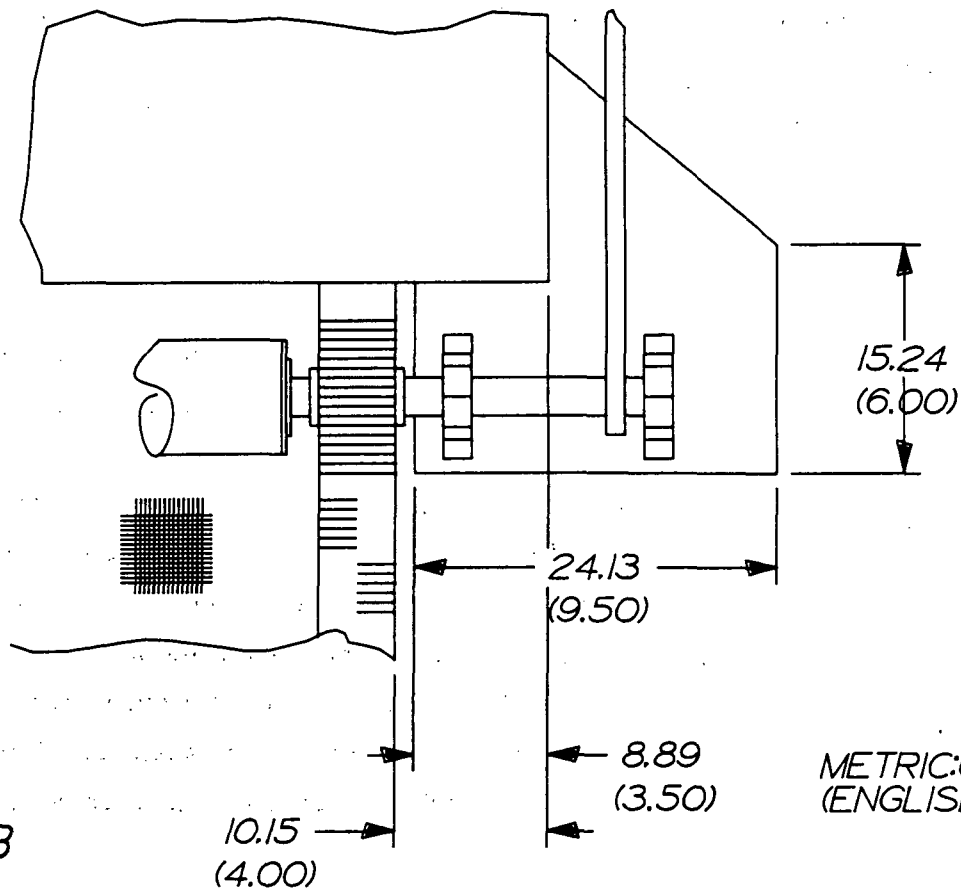
THRUST  
BEARING

1.27 (.50)  
HONEYCOMB  
SUPPORT PANEL

SLAVE  
SPROCKET

METRIC:CM  
(ENGLISH:INCHES)

FIGURE 4.3A  
FRONT VIEW



METRIC:CM  
(ENGLISH:INCHES)

FIGURE 4.3B  
TOP VIEW

Figure 4.3 LBR DRIVE SYSTEM: REAR END

is comprised of nylon longitudinal and cross members ultrasonically - or adhesively-bound to the 0.076 cm (0.03 inch) thick mesh structure.

#### 4.6 Structural Components

The outer structure of the LBR point design is comprised of rigid, lightweight, aluminum honeycomb panels which have a nominal thickness of 1.27 cm (0.5 inch). These panels are an adhesively bound, low density, high strength sandwich structure ideal for space applications.

The internal honeycomb can be machined to virtually any shape. Metal inserts designed for internal attachments (i.e., bath containment seals) or rigid fastening procedures may be easily implanted. Composite materials such as Kevlar, fiber reinforced plastics, and Nomex have been employed to develop honeycomb sandwich structures for other applications. It is however, not known if these materials can withstand prolonged exposure to the ultraviolet radiation of space. Since aluminum honeycomb has been used extensively by the Hexcel and Parsons Corporations in similar space structural applications, this material was chosen to serve as support panels for the LBR point design.

#### 4.7 Deployment System

The deployment system of the LBR involves a departure from the Phase I effort. The stuffing box storage device has been replaced by a mechanism in which the belt is wrapped upon itself in the stowed position. Figure 4.4 shows an isometric view of the LBR featuring the stowage mechanism. In the current design the roller upon which the belt is coiled will be spring loaded in the stowed position. Upon deployment in space, restraining bolts will be released resulting in the uncoiling of the belt. Motion will then be imparted to the belt by the drive motors which, in the absence of an acceleration field, will result in the belt attaining the circular shape associated with its operation as a radiator.

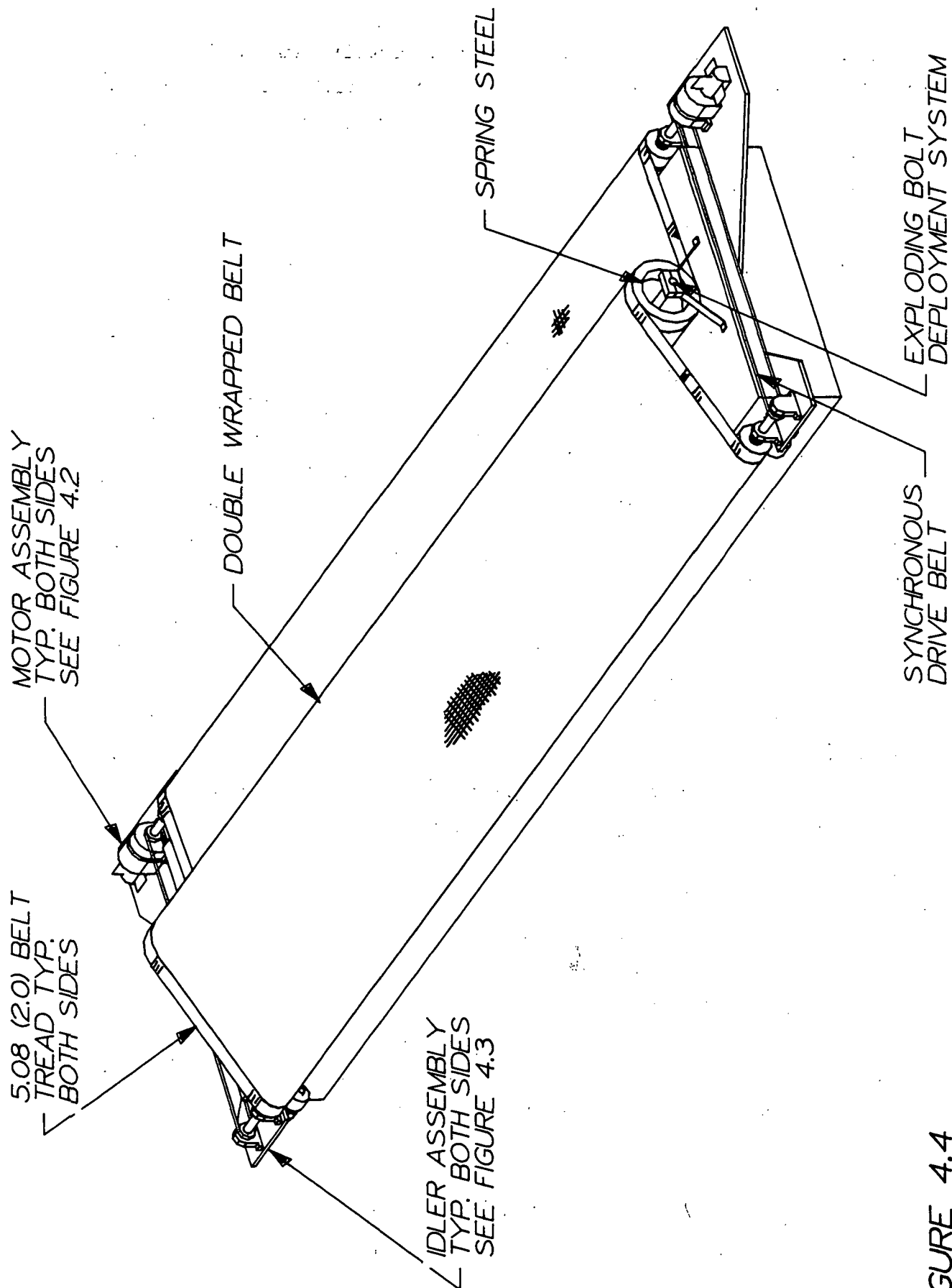


FIGURE 4.4  
ISOMETRIC VIEW OF  
LBR IN STOWED POSITION

The dynamics of belt deployment are quite complex and will require additional analytical and experimental study to arrive at appropriate designs. The approach described above, however, provides a reasonable basis for defining preliminary designs and accounting for the size and mass of one of the deployment candidates.

#### 4.8 System Mass Breakdown

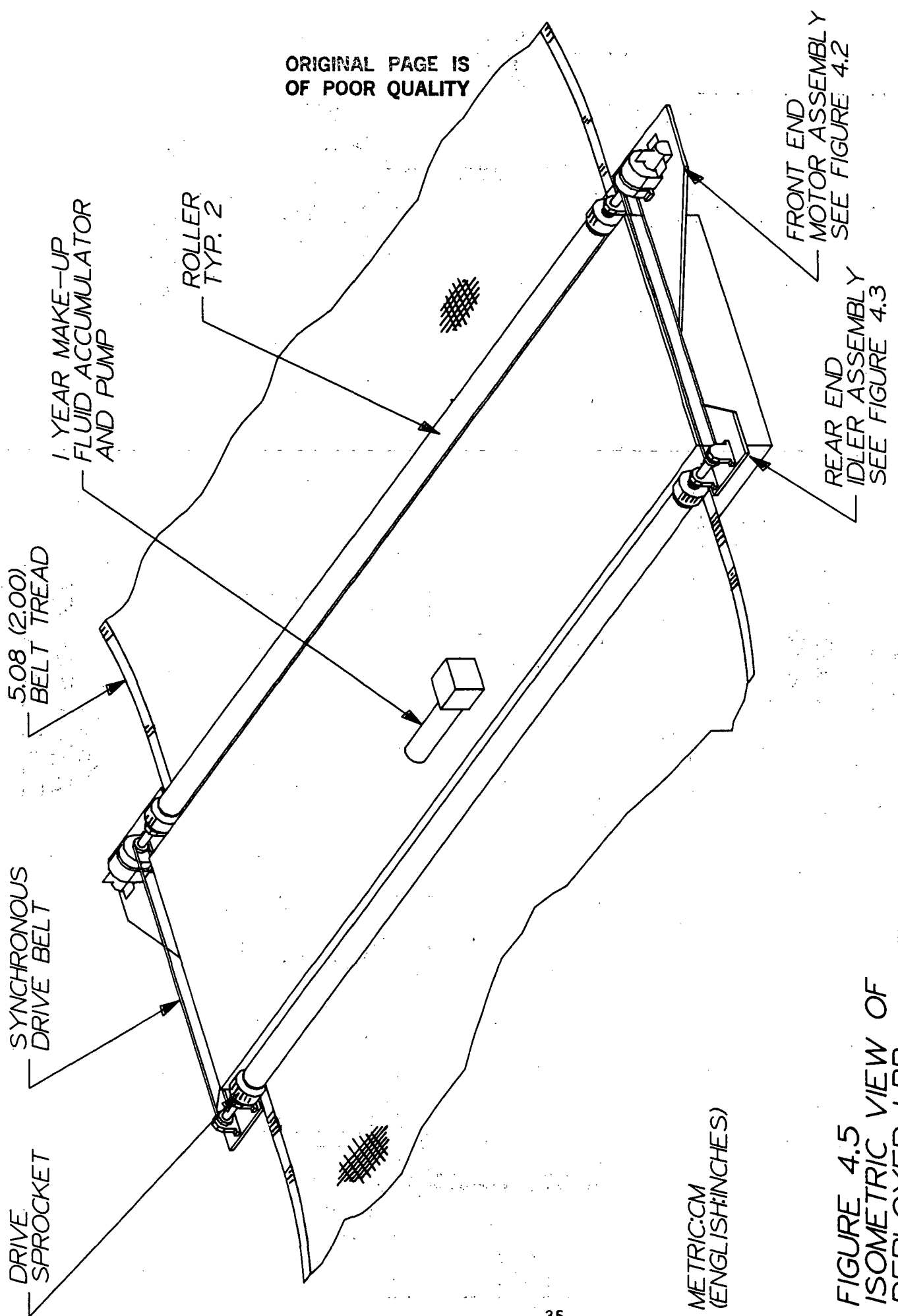
Figures 4.5, 4.6 and 4.7 present isometric, top and side views of the revised LBR point design in the deployed position. These drawings were constructed on the Arthur D. Little computer aided design system. Table 4.2 presents a mass breakdown of all aforementioned salient LBR components. From this table, it may be seen that the LBR working fluid represents over 50% of the total system mass, while structural components (i.e., interfacing exchanger, seals, support panels) comprise the remainder.

The specific mass associated with the updated LBR design (defined as total system mass per unit radiating area) is  $1.28 \text{ kg/m}^2$  which is only 26% of conventional heat pipe or pumped fluid loop systems. Furthermore, it should be stressed that this design represents one of the few attempts to take into account all the subsystems associated with an advanced radiator concept including:

- The radiating section itself
- Interface heat exchangers
- Stowage volumes and mechanisms
- Operating ancilliary equipment (motors, etc.)

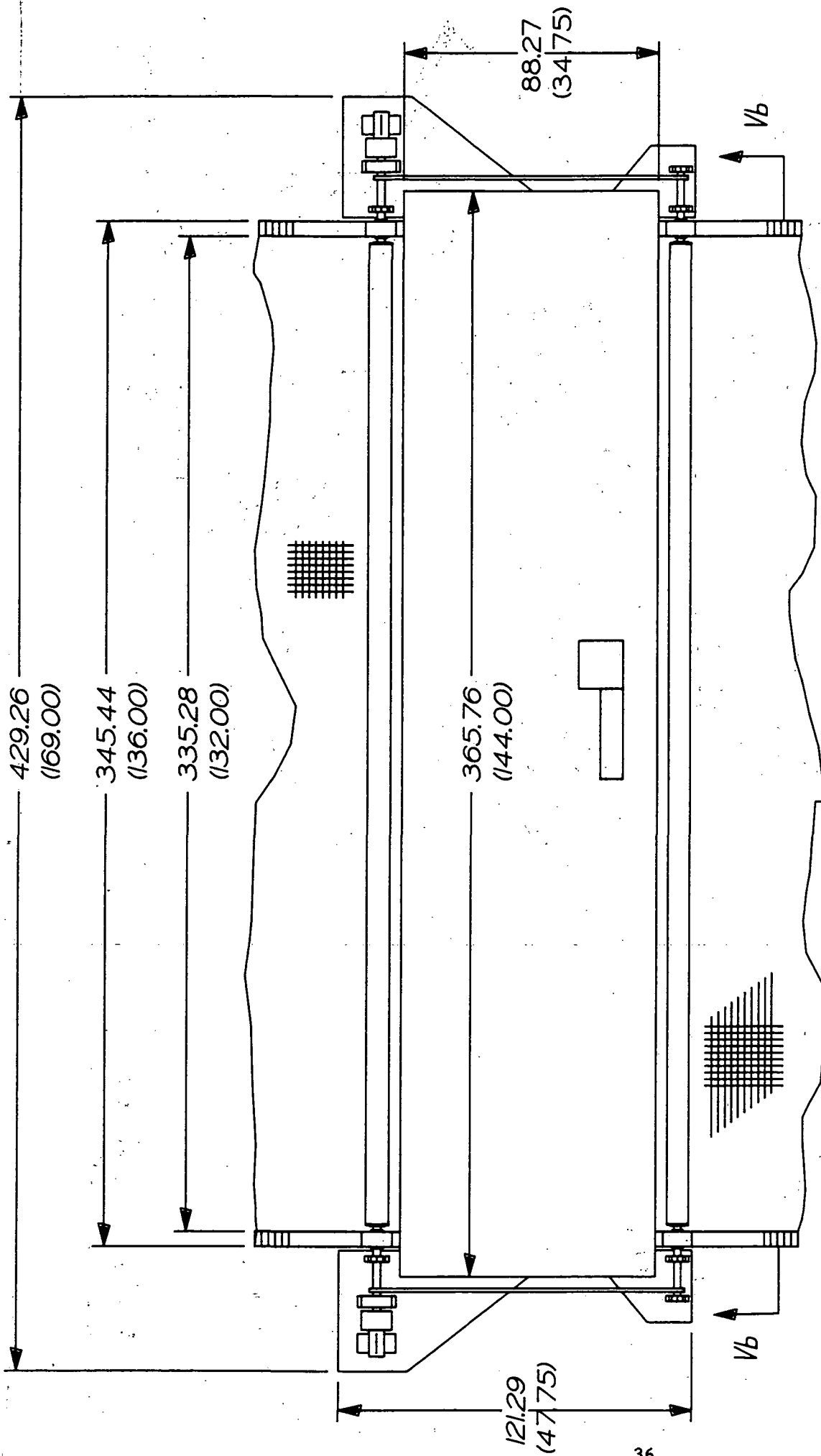
As indicated above, realistic assessments and comparisons of radiator systems must take all the above into consideration.

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FIGURE 4.5  
ISOMETRIC VIEW OF  
DEPLOYED LBR



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FIGURE 4.6  
TOP VIEW OF  
DEPLOYED LBR

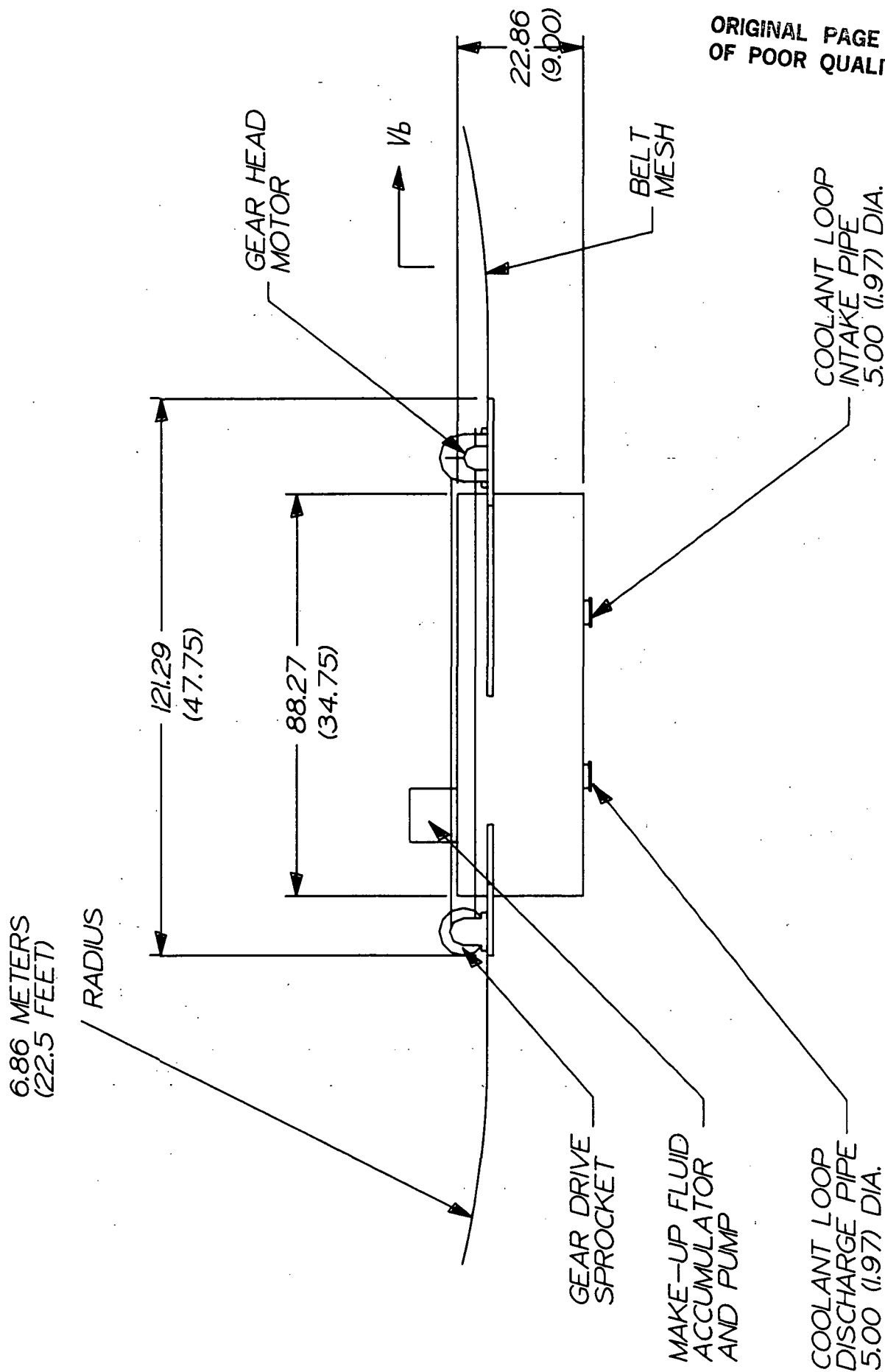


FIGURE 4.7  
SIDE VIEW OF  
DEPLOYED LBR

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Table 4.2

ESTIMATED MASS BUDGET FOR LBR POINT ENERGY  
USING SANTOVAC 6 OVER 300-330 K TEMPERATURE RANGE

Component	Salient Dimensions	Materials Employed	Component Mass
1. Belt/Fluid Combination	0.076 cm(0.03") thick Belt	Nylon Screen Mesh and Diffusion Pump Oil	132.6 kg
2. Bath Heat Transfer and Make-Up Fluid	Bath Volume: 0.036 m <sup>3</sup>	Santovac Oil	50.0 kg
3. Interface Heat Exchanger	L = 0.73 m; w = 3.50m	All parts constructed of Aluminum	
o Heat Exchange Plates(2)	t = 0.127 cm(0.05 in)		20.0 kg
o Header (2 x 2)	-		3.0 kg
o Tubes (2 x 67)	t = 0.089 cm(0.035 in)		10.5 kg
o Channel Support (2)	h = 1.3 cm		0.5 kg
o Interface Coolant Loop Piping	-		5.0 kg
4. Containment Seals	-	Aluminum Honeycomb, Plastics and Rubber	
o Double Labyrinth	w = 3.50 m, L = 0.04 m,		8.0 kg
o Brush Seal	h = 0.02 m		1.0 kg
5. Drive System		Aluminum, nylon, and reinforced rubber for belt drive	
o DC Gear Head Motors (2)	-		14.0 kg
o Sprockets (4)	D = 10 cm, L = 5 cm		2.0 kg
o Aluminum Rollers (2)	D = 7.6 cm, L = 3.3 m		4.5 kg
o Structural Support (4)	-		5.0 kg
o Misc. Shafts, Belts, and pulleys.	-		5.0 kg
6. Support Panels	1.27 cm Nominal thickness	Aluminum Honeycomb Laminate	28.0 kg
7. Deployment System	0.002 m <sup>3</sup> Spring Steel Member	Spring Steel (0.051 cm thick)	35.0 kg
8. Control System	-	-	3.0 kg
9. Fastners, Supports and Misc.	-	Aluminum, Stainless steel, organic adhesives	5.0 kg
Total:			332.1 kg

Notes

D = diameter      L = length  
t = thickness      w = width

## 5.0 LIFE LIMITING FACTORS

### 5.1 Introduction

The useful life of the LBR should be many years with proper design of moving components and selection of proper materials. Nevertheless, as with any system subjected to the harsh environment of space and operation at elevated temperatures there are life limiting mechanisms present. For the LBR these include the following factors:

- o The life of its active elements which in the current designs are the drive motors.
- o Wear taking place on rubbing surfaces such as the bath containment seals, the belt drive wheels, and the belt itself.
- o Material degradation due to such factors as:
  - Incompatibility between the belt material and working fluid.
  - Changes in material properties (working fluid, belt material, etc.) due to ultraviolet degradation or chemical reactions with species found in space (albeit only on a molecular level)
- o Mechanical damage due to impact by meteorites.

Even within the context of the low level conceptual design efforts undertaken to date, attention has been given to ensuring that the designs and material selections were consistent with long life despite the presence of the above factors. As the LBR program continues into more detailed analytical design and testing phases these life limiting factors must be examined in more detail.

Several observations on each of these factors are presented below:

### 5.2 Motor Life

The only active electro-mechanical components within the LBR are the drive motors which propel the belt through interface heat exchanger. During this

program several companies were contacted to identify motors designed for long term operation in a space environment. The design assumes the use of low speed (100 RPM) motors such as currently manufactured by the MPC Corporation. Manufacturers contacted suggested that these motors could have useful lives of over 10,000 hours. Furthermore, two such motors were assumed either one of which can operate the system thereby providing redundancy. Additional efforts to identify and test belt drive motors would however, certainly be included in future program phases.

### 5.3 Belt/Seal Wear

In order to limit loss of working fluid from the interface heat exchange bath, the current design assumes the use of a lightly loaded series of seals at the entrance and exit gaps. In low temperature service these seals would be low friction non metallic-materials such as currently used in Stirling engines and cryogenic cooling equipment. When lightly loaded the wear rates on both the seal and their mating surfaces (the belt), even in an unlubricated environment, approach being negligible which should lead to very long life. The use of an oil as the low temperature working fluid directly provides lubrication further reducing the potential for wear on these surfaces.

Higher temperature applications involving liquid metals can use the same sealing philosophy albeit with different seal materials - possibly carbon based composites if they are determined to be compatible with the working fluids.

### 5.4 Material Degradation

It is essential to identify working fluid, belt, and heat exchanger material combinations which are both compatible with each other (i.e. no corrosion) and can withstand the harsh environment of space (ultraviolet radiation, etc). To date the program has not dealt extensively with these issues. For example, the long term stability of the low vapor pressure oils in a space environment has

not been determined. Similarly for high temperature applications the compatibility of lithium with candidate belt materials would have to be determined. For these reasons, long term material compatibility and degradation testing would have to be part of a long range development program.

#### 5.4 Micro-Meteorite Damage

Impact by Micro-meteorites could damage the interface heat exchanger unit or the belt itself. The first form of damage will be made unlikely by the micro meteorite impact resistant aluminum honeycomb enclosure surrounding the heat exchanger and the bath material. This assembly should be less prone to such damage than the large exposed surface of pumped or heat pipe radiator assemblies.

The belt/liquid area itself should also be relatively impervious to micro meteorite damage. However one of the primary concerns over such damage would be the impact on the effectiveness of the heat exchanger seals as the damaged section is drawn through the bath. The impact of mesh structure materials and design on susceptibility to micro-meteorite damage will be an important issue in future program phases.

Based on the above considerations, it appears that the LBR system may be less prone to micro-meteorite damage than the alternatives.

## CHAPTER 6

### 6.0 CONCLUSIONS AND PROGRAMATIC LBR DEVELOPMENT PLANS

#### 6.1 General Conclusions

The LBR shows good promise of resulting in a light weight, stowable, and easily deployed radiator system over broad temperature range. This has been demonstrated by the earlier Phase I program and further confirmed in this study. Important conclusions of these studies include:

- o Complete LBR system masses less than 30 percent of conventional heat pipe or pumped fluid radiators can be conceptually achieved.
- o The parasitic power requirements associated with moving the belt through the fluid contained in the heat sink heat exchanger are low. In fact, for liquid metals the parasitic power requirements are close to negligible.
- o A readily stowable configuration with several options for automatic space deployment are possible.
- o Inherent internal damping mechanisms exist which will tend to enhance the dynamic stability of the LBR.

In addition, limited experimental work which included pulling liquid belts using heat transfer oils and liquid gallium further demonstrated the potential for this concept.

The excellent progress to date has been accomplished through very modest programs totaling approximately 1 person-year of effort. During these programs no major barriers were identified which would prevent the development of a radiator system by the early to mid 1990's assuming a focused development effort. The following outlines a new program to undertake such a development with clearly defined interim goals and check points. This program is divided into four (4) phases:

Phase 1: Technical Issues Identification and Resolution

Phase 2: Proof of Concept Test System

Phase 3: Space Shuttle Experiment

Phase 4: Space Flight Design Definition

The Phase 1 effort would require about 9 months and would lay the groundwork for the Phase 2 Proof of Concept experiments. The Proof of Concept Tests would include the assembly of a LBR system for operation in the vacuum facilities of NASA Lewis as well as zero gravity tests in the drop tunnels to verify meniscus formation in a zero G environment. These tests would, in turn, lay the groundwork for a Space Shuttle Experiment which could be flight ready within 3 years of program initiation.

The key to meeting this overall objective is to mount a focused effort in the aforementioned Phase I of the new program to identify potential technical issues and to expeditiously resolve them by a combined analytical and experimental efforts. The Phase I program is described in more detail in the following section.

## 6.2 Phase I Program Design

The earlier programs served to define the operational characteristics of a LBR for a range of operating conditions and the potential for the concept to meet space requirements. The objectives of this next phase will be to:

- o Investigate in more detail the complex dynamic interactions of the moving belt and the spacecraft.
- o Explore how the use of an LBR will impact on the performance and optimum operating conditions of candidate space power systems.
- o Experimentally verify the ability to contain the liquid heat transfer material in the bath using sealing arrangements defined in this current study.

- o Define in more detail belt construction and materials when using liquid metals as the heat transfer media.

Achieving this combination of objectives will lay the groundwork for developing a Proof of Concept Experiments which can be tested in vacuum and zero G drop tank facilities at NASA Lewis. The individual tasks of the Phase 1 program are outlined below.

#### 6.2.1 Task 1: Dynamic Stability and Deployment

The dynamics of the moving belt can be quite complex, particularly when vibrational modes of motion are superimposed on the normal belt motion. During this task the analyses initiated earlier work will be extended and refined by both analytical and experimental means.

##### Task 1.1 Analytical Refinements

Estimating the important physical constants which impact on the analysis as a function of belt configuration (web size, etc.), and working fluid parameters will be examined. These constants include:

- o Stiffness
- o Characteristic wave speeds
- o Damping coefficients

Based on these analytically derived constants, the dynamic motion of the LBR using different working fluids of interest will be estimated.

##### Task 1.2 Experimental Verification

The vibrational motion of the composite liquid/belt structure is dependent on many physical variables and resultant analytical projections can only indicate major trends. During this task a prototype section of the LBR (several feet long) under tension forces similar to that in a space environment will be subjected to periodic loads. The resultant motion (waveform, magnitudes,

damping, etc.) will be measured and compared to analytical projections. This will serve to verify basic trends postulated by the analyses and allow for further analytical refinement based on experimental results.

#### 6.2.2 Task 2: Power Systems Optimization

The optimization of power system design and operating conditions will depend significantly on the weight characteristics of radiators. Conventional radiator techniques have masses upward of 30-50 percent of entire power system mass. The relatively high mass of radiators results in high heat rejection temperatures which, in turn, lower power system efficiency.

The much lower mass of the LBR could significantly impact on optimum power system operating conditions with the general trend being to lower heat rejection temperatures. This in turn would lead to:

- o Increased power system conversion efficiencies.
- o Lowered power system and associated fuel source (nuclear, solar, etc.) mass.

During this task, the above issues will be addressed for three of the power systems being considered by NASA:

- o Closed cycle Brayton engines
- o Stirling engines
- o Liquid metal Rankine

For all systems, both nuclear and solar energy sources will be considered. Size and mass parameters for power cycles and heat sources developed by NASA will be utilized in undertaking minimum system mass optimization studies.

#### 6.2.3 Task 3: Liquid Bath Containment

One of the key technical issues for implementing the LBR concept is the ability to contain the liquid in the interface heat exchanger despite the viscous forces



imposed by belt movement. Analyses conducted in the initial and current studies indicated that this issue could be resolved by proper design of exit slot dimensions and the use of wiper seals. This task will verify that this represents a viable approach through experimental analysis. This experiment will simulate the forces on the bath liquid in a zero G environment while the mesh is drawn through an exit slot.

Tests will be conducted both for a heat transfer oil and for liquid tin to cover the range of operating conditions for an LBR.

#### 6.2.4 Task 4: Belt/Liquid Material Definition and Compatibility

Limited wettability tests of candidate belt/fluid material combinations at room temperature (oils and gallium) as well as emissivity measurements of selected fluid materials (oils and gallium) have been conducted (Reference I). This effort will be extended to deal with similar issues for the higher temperature candidate materials, lithium and tin. It will include:

- o Material studies based on the literature and analyses to define what combination of belt/fluid materials will be chemically compatible and have the required wettability characteristics.
- o Material studies based on the literature to identify potential alloys which will allow for modifying heat rejection temperatures (still in the heat of fusion mode) and which might have higher values of emissivity.
- o Material studies to characterize potential impurities in liquid metals which would raise emissivity levels and have long term chemical stability in a high vacuum environment.

The above will help define belt and fluid bath material candidates for use in design studies and proof of concept experiments at higher temperature levels.

#### 6.2.5 Task 5: Lithium Emissivity

Lithium is potentially the most attractive LBR material for use at intermediate temperature levels of major interest for space power applications. The primary issue relative to the use of this material is its emissivity in the solid state and whether this emissivity can be enhanced by highly stable impurities. In this task the emissivity measurement apparatus and associated handling equipment at Arthur D. Little will be modified to work with lithium at its melting point. Emissivity measurements on both pure lithium and lithium with known impurities (oxides) will be made to determine if sufficiently high emissivity levels to be of interest can be obtained or at least projected.

#### 6.2.6 Task 6: System Size Limitations

The heat rejection rate used in the earlier parametric studies and conceptual designs was 75 kW (thermal). Many space missions in the future will involve rejecting much larger quantities of heat as mission power needs increase. During this task the impact of scaling up the capacity of LBR will be assessed taking into account such issues as:

- o The possible need to increase belt speeds as size increases.
- o The reduction in view factors to space if belt widths increase in order to increase area.
- o The option for multiple belt deployment so that the end result is a modular system whereby increased heat rejection capacity implies using a larger number of LBR systems.

These analyses and associated conceptual designs will be undertaken for three heat rejection rates, 150 kW, 500 kW, and 1000 kW. This range will display the potential for scaling up the LBR concept to serve all, or most, thermal requirements over the coming decades.

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16. Abstract  The Liquid Belt Radiator (LBR) is an advanced concept developed to meet the needs of anticipated future space missions. A previous study completed by Arthur D. Little, Inc. for the NASA-Lewis Research Center (contractor report CR-174807) documented the advantages of this concept as a lightweight, easily deployable alternative to present day space heat rejection systems. The program documented in this report represents a continuation of the aforementioned work. The technical efforts associated with this study concentrated on refining the concept of the LBR as well as examining the issues of belt dynamics and potential application of the LBR to intermediate and high temperature heat rejection applications. A low temperature point design developed in previous work was updated assuming the use of diffusion pump oil, Santovac-6, as the heat transfer media. Additional analytical and design effort was directed toward determining the impact of interface heat exchanger, fluid bath sealing, and belt drive mechanism designs on system performance and mass. The updated design supported the earlier result by indicating a significant reduction in system specific system mass as compared to heat pipe or pumped fluid radiator concepts currently under consideration (1.3 kg/m <sup>2</sup> versus 5 kg/m <sup>2</sup> ).					
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